# Presentation for DOE Site Visit

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# Research Programs

- New physics beyond the Standard Model
  - New models (scenarios) for electroweak symmetry breaking
  - Precision electroweak and other experimental constraints
  - Experimental signatures of new physics
- Cosmology from the particle physics perspective
  - New candidates for dark matter
  - Dark energy or modification of gravity
  - Models of inflation

# Introduction

New physics is expected at the TeV scale and will be discovered at LHC and other upcoming experiments.

- Hierarchy problem requires new physics to cut off the quadratically divergent contributions to the Higgs mass^2 from the SM interactions at or below ~ 1 TeV.

- Dark matter in the universe is currently the strongest experimental evidence for new physics beyond the SM. It also points to the TeV scale as a WIMP of TeV mass gives the right thermal relic aboundance.

$$\Omega_{\rm WIMP} \sim \left(\frac{1}{10^2\alpha}\right)^2 \left(\frac{m_{\rm WIMP}}{1\,{\rm TeV}}\right)^2$$

# Introduction

Supersymmetry (SUSY) has been the favorite new physics beyond the SM. However, there are many new candidate theories proposed in recent years.

- Extra dimensions: Flat or Warped, gravitation only or SM propagating
- Higgs as a PNGB: Little Higgs, Twin Higgs
- No Higgs: Technicolor, Higgsless
- Combinations of these ideas

# Introduction

Many of these new theories can also provide good dark matter candidates, if they contain some new (discrete) symmetries.

- Universal Extra Dimensions: KK-parity

  Appelquist, HC, Dobrescu;  HC, Matchev, Schmaltz

- Little Higgs Theories with T-Parity

  HC, Low

Such a new symmetry is also highly motivated from the precision electroweak constraints: New particles charged under the new symmetry do not contribute to EW observables at tree level.

# Landscape of Alternative Theories

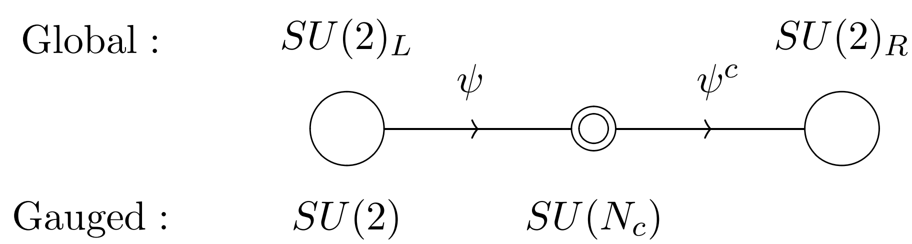
Among so many possible theories and variations among each scenario, which ones deserve more detailed phenomenological studies in preparation for the LHC?

It would be beneficial if there is a unified approach to many different theories.

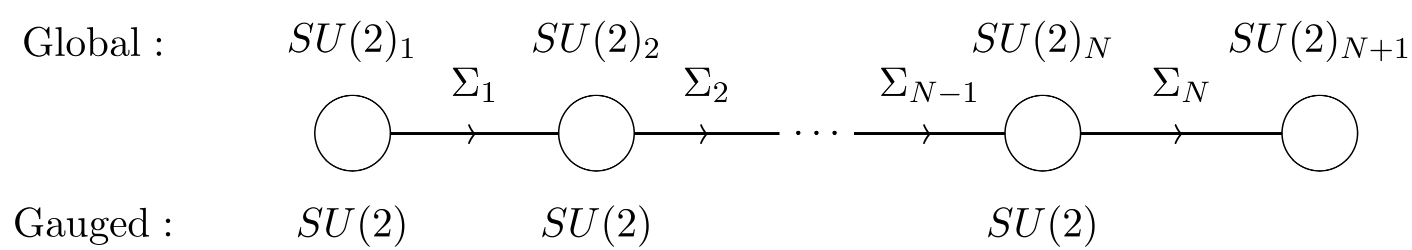
In fact, most of the known non-SUSY models can be represented or approximated by moose diagrams.

# Landscape of Alternative Theories

## Technicolor:

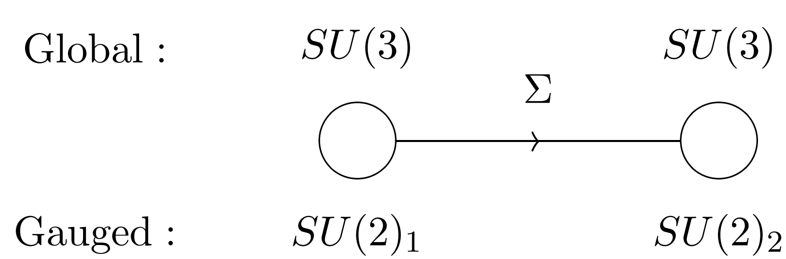



## Extra dimensions: by deconstruction




Warp factor can be represented by different Goldstone decay constant on the links.

## Little Higgs:



# Landscape of Alternative Theories

Mooses are a convenient framework to describe spin-1 and spin-0 degrees of freedom.

Precision EW constraints indicate that the scale of strong dynamics may be out of the reach of the LHC, and in the case of extra dimensions, LHC will be able to discover only a few KK modes at most.

At low energies (accessible to LHC) , most non-SUSY models can be well represented by some simple moose models, and many models can be described by the same moose diagram.

# Little Higgs Theories

- Higgs field(s) are pseudo-Nambu-Goldstone bosons (PNGBs) of a spontaneouly broken global symmetry G $\rightarrow$ H.
- Higgs mass is protected from one-loop quadratic divergence so that the cutoff can be pushed up to ~10 TeV.
- The quadratic divergences are cancelled by new particles which are partners of the SM top quark, gauge bosons and Higgs. Unlike SUSY, they have the same spins as the SM particles.

# Little Higgs Theories

Many different little Higgs models bases on various $G/H$ and the gauged subgroup $F \subset G$.

(The unbroken gauge group: $I = F \cap H$ ( =SM))

**Minimal moose:**

$$SU(3)^2/SU(3)$$
$$F = (SU(2) \times U(1))^2$$

Arkani-Hamed et al, hep-ph/0206020

**Littlest Higgs:**

$$SU(5)/SO(5)$$
$$F = (SU(2) \times U(1))^2$$

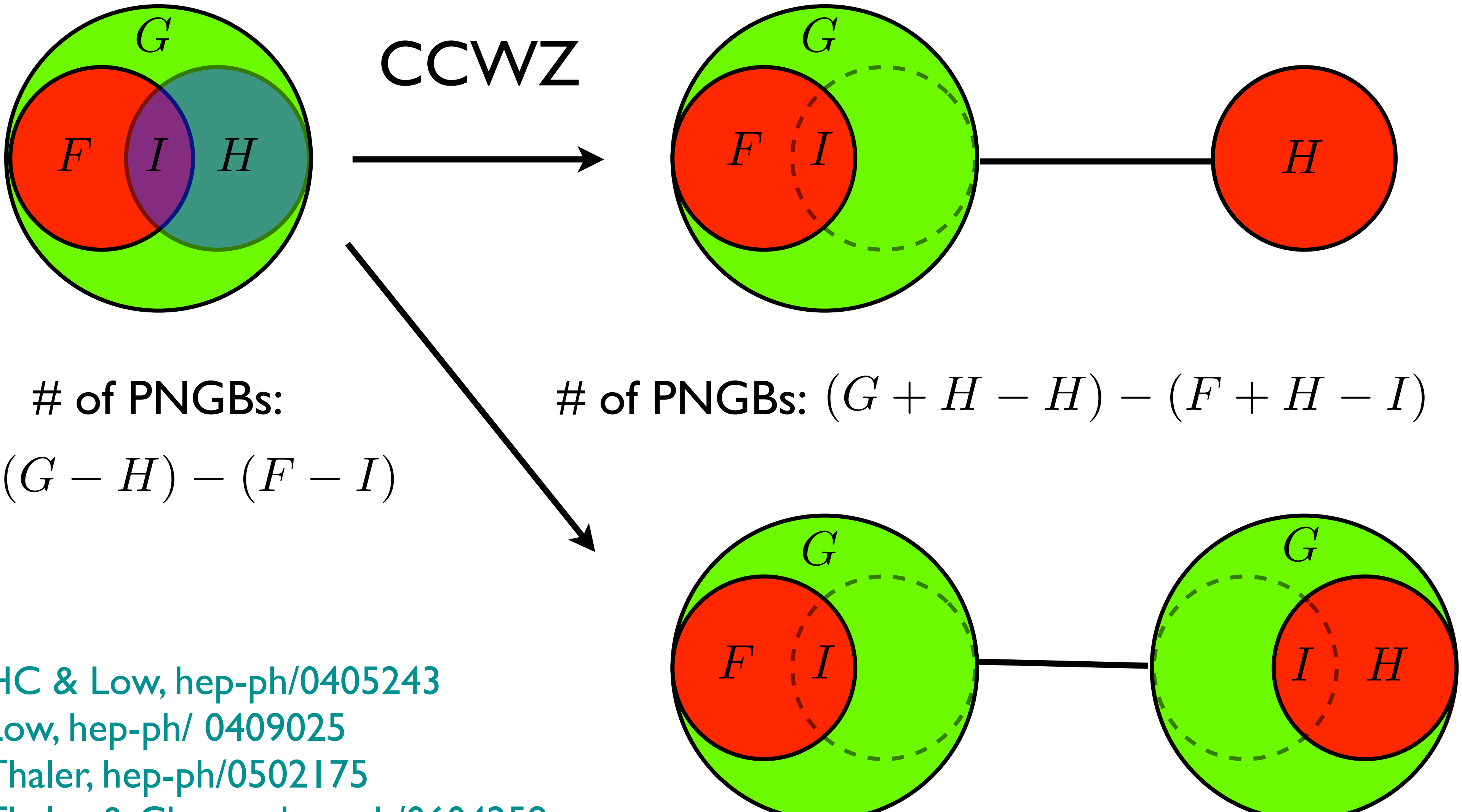
Arkani-Hamed et al, hep-ph/0206021

**Simple little Higgs:**

$$[SU(3)/SU(2)]^2$$
$$F = SU(3)\ (\times U(1))$$

Kaplan & Schmaltz hep-ph/0302049

Using CCWZ (or hidden local symmetry, AdS/CFT) they can all be converted into moose models.




# of PNGBs:

$$(G - H) - (F - I)$$

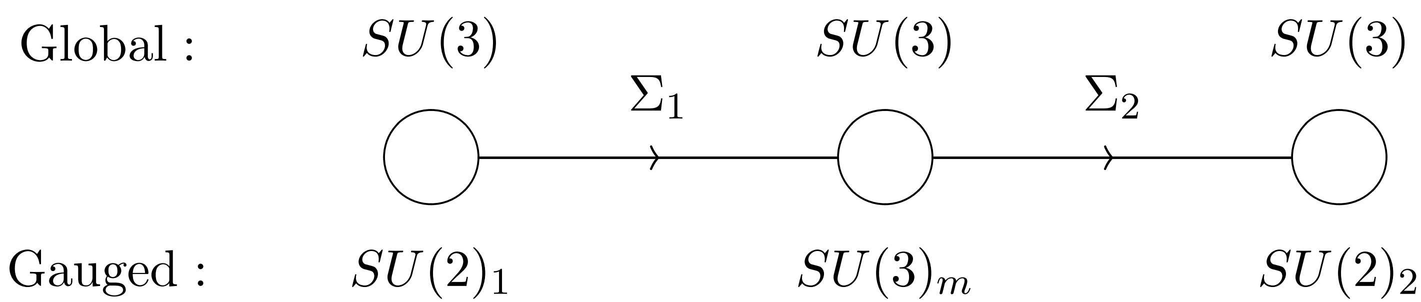
# of PNGBs: $(G + H - H) - (F + H - I)$

HC & Low, hep-ph/0405243
Low, hep-ph/ 0409025
Thaler, hep-ph/0502175
Thaler & Cheung, hep-ph/0604259

# of PNGBs: $(G + G - G) - (F + H - I)$

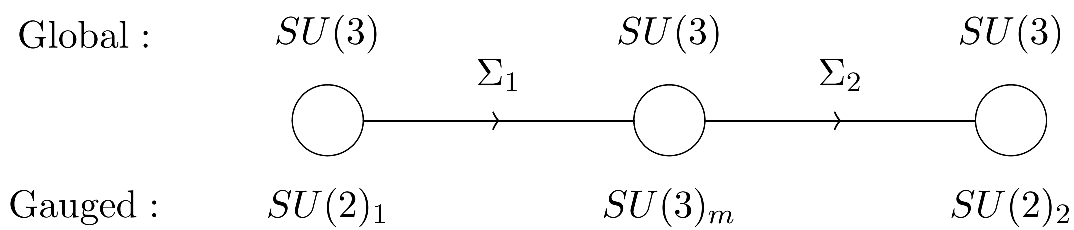
# A Universal Moose Model (Little M-Theory)

(HC, Thaler, Wang)



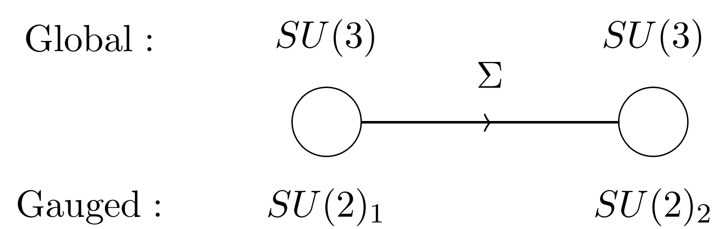

The above moose diagram can describe several very different looking models by taking various limits.

# Little M-Theory




- Simple little Higgs: $g_{1,2}$ of $SU(2)_{1,2} \to \infty$
- Minimal moose: $g_m$ of $SU(3)_m \to \infty$

  The middle site can be integrated out.

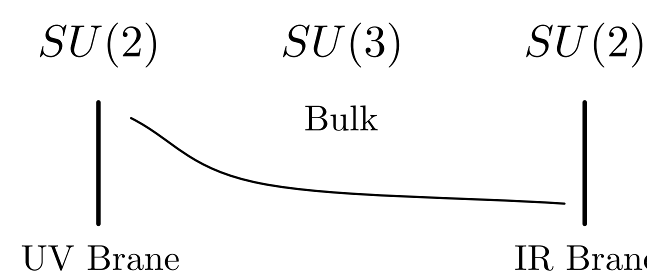



- T-parity: $g_1 = g_2,\ \langle\Sigma_1\rangle = \langle\Sigma_2\rangle$

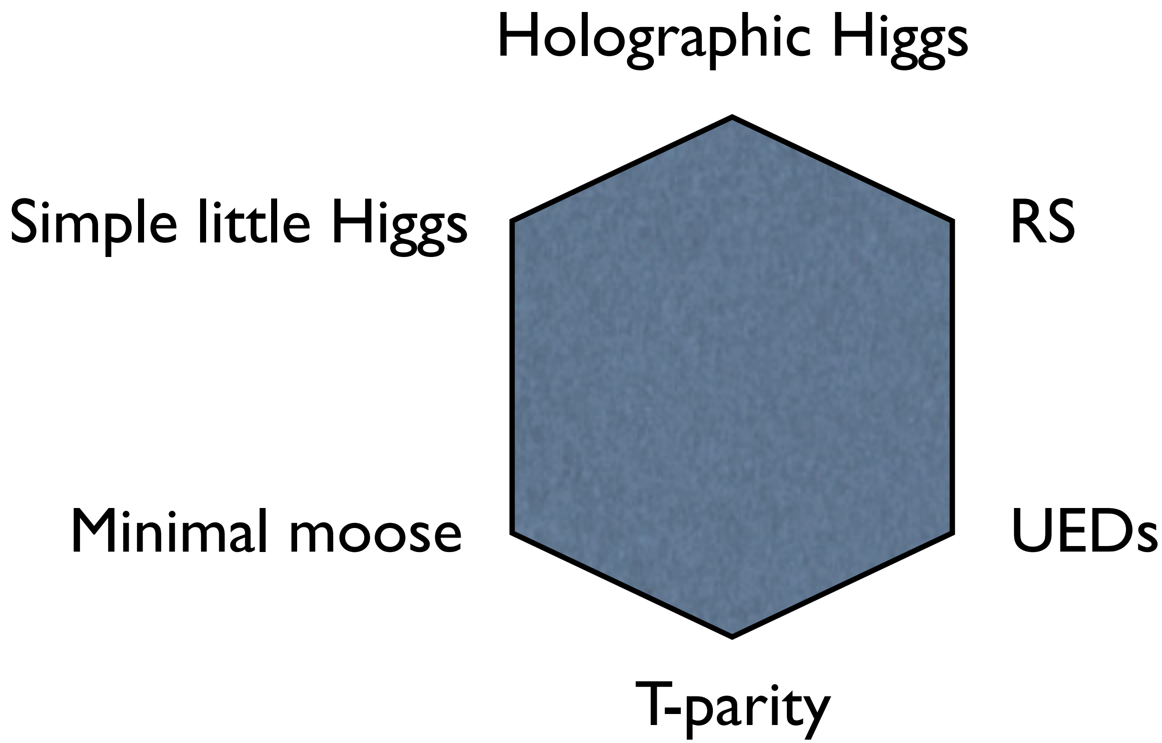
  HC & Low

- Holographic PNGB Higgs:

  Contino, Nomura & Pomarol



# Little M-theory



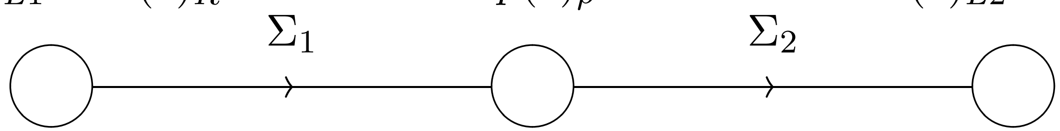

## M=Moose

It also reveals a larger model space than the individual corners.

# Little M-theory

## A representative model: Sp(4)/SO(4) moose with a custodial SU(2) symmetry

| | | | |
|---|---|---|---|
| Gauged : | $SU(2)_{L1} \times U(1)_R$ | $Sp(4)_\rho$ | $SU(2)_{L2} \times U(1)_R$ |




| | | | |
|---|---|---|---|
| Quarks : | $Q_1, Q_1^c$ | $Q_m$ | $Q_2, Q_2^c$ |
| Leptons : | $L_1, L_1^c$ | $L_m$ | $L_2, L_2^c$ |

$$Q_i = \begin{pmatrix} q_i \\ 0 \\ 0 \end{pmatrix}, \quad Q_i^c = \begin{pmatrix} q_i^c \\ t_i^c \\ b_i^c \end{pmatrix}, \quad Q_m = \begin{pmatrix} q_m \\ t_m \\ b_m \end{pmatrix}, \quad Q' = \begin{pmatrix} 0 \\ t' \\ b' \end{pmatrix}, \quad Q'^c = \begin{pmatrix} 0 \\ t'^c \\ b'^c \end{pmatrix},$$

$$L_i = \begin{pmatrix} \ell_i \\ 0 \\ 0 \end{pmatrix}, \quad L_i^c = \begin{pmatrix} \ell_i^c \\ \nu_i^c \\ \tau_i^c \end{pmatrix}, \quad L_m = \begin{pmatrix} \ell_m \\ \nu_m \\ \tau_m \end{pmatrix}, \quad L' = \begin{pmatrix} 0 \\ \nu' \\ \tau' \end{pmatrix}, \quad L'^c = \begin{pmatrix} 0 \\ \nu'^c \\ \tau'^c \end{pmatrix}.$$

# Phenomenology

It has rich phenomenology, can serve as a framework for benchmark models as the MSSM for SUSY.

- W', Z'
- $W_R$, X (off-diagonal) gauge bosons
- "KK" quarks and leptons
- Extra PNGB scalars
- T-parity
  - Dark matter (being studied by a student, Cai)
  - Similar collider signals as SUSY

# SUSY vs Alternatives

With a dark parity, many alternative theories and SUSY will have similar collider signals at the LHC (jets/leptons + missing energy).

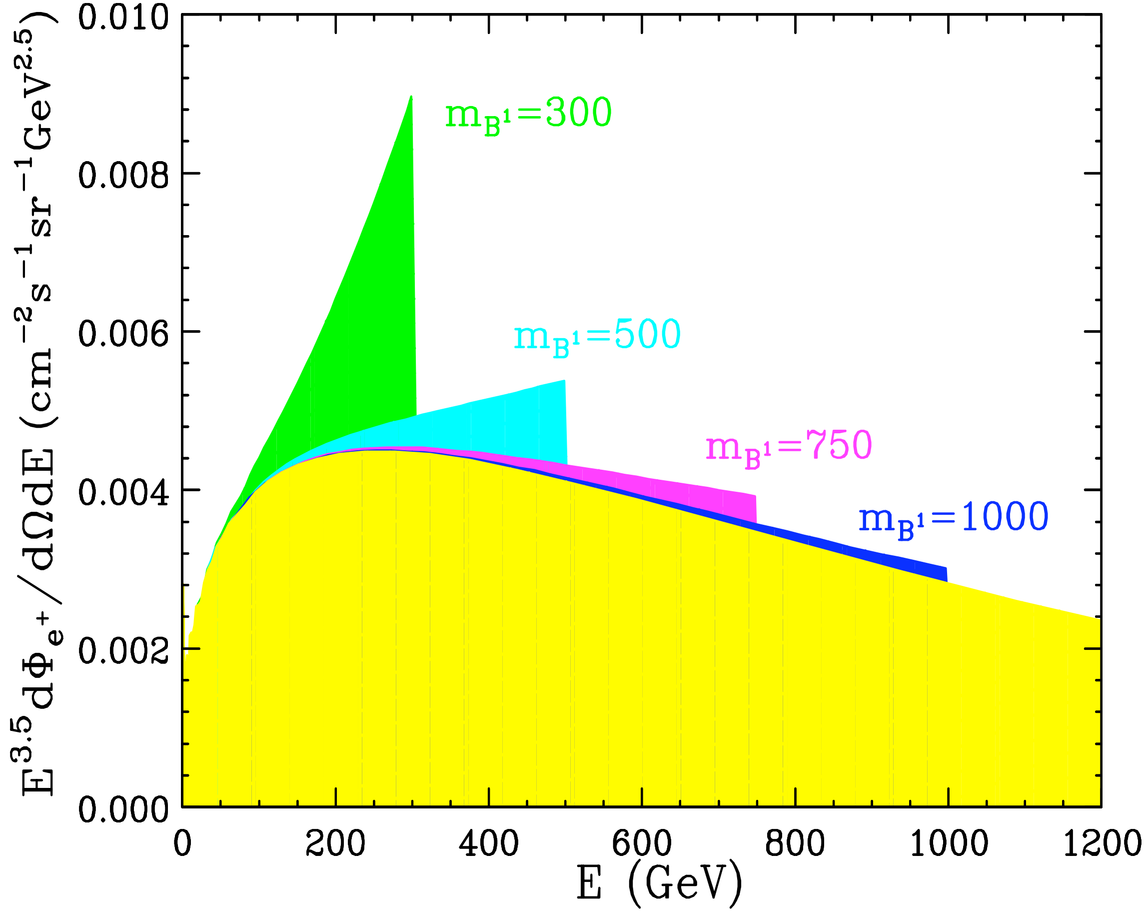
To tell what the new physics after the discovery, it's important to find ways to distinguish different scenarios. In particular, we want to measure the spins of the new particles in addition to their masses and couplings.

- Dark matter searches may provide some information.
- It's a challenge at the LHC.

# Indirect Dark Matter Detections

- Predicted positron signals

(Cheng, Feng, Matchev, hep-ph/0207125)




- SUSY: helicity-suppressed annihilation amplitudes
- A peak in the $e^+$ spectrum:
  - A smoking gun for $\gamma_1$ dark matter
  - can rule out neutralinos as the source

# Measuring Spins at LHC

(HC, Gunion, Marandella, McElrath &Han)

With 2 or more missing particles in a process, it's difficult to reconstruct the spins of the particles involved in the production and decays.

There have been attempts by looking at various invariant mass distributions of the observed particles. (e.g., Barr; Smille & Webber; Datta, Kong & Matchev; Meade & Reece; Alves, Eboli & Plehn; Wang & Yavin;...)

# Measuring Spins at LHC

(HC, Gunion, Marandella, McElrath &Han)

We are currently investigating a different approach: By finding intersections of consistent regions of all events, one can reconstruct the full kinematics of each event.

Not only does it allow us to measure the masses (not just mass differences) of the produced particles, but one can also look at the angular distributions in any rest frame of the produced particles by performing an appropriate boost.

More details will be given in Bob McElrath's talk.

# Conclusions

It’s an exciting time for particle physics. Many mysteries of our universe will finally be unveiled, including the origin of the electroweak symmetry breaking, the nature of the dark matter, and possible extra (bosonic or fermionic) spacetime dimensions.

We are fully engaged in the efforts of uncovering the true underlying theory, including investigating new mechanisms and models for the electroweak symmetry breaking, studying their experimental consequences, and looking for ways to identify new physics after the discovery.